

*Boundary Lubrication.—The Temperature Coefficient.*

By W. B. HARDY, Sec.R.S., and IDA DOUBLEDAY.

(Received June 20, 1922.)

(Report to the Lubrication Research Committee of the Department of Scientific and Industrial Research.)

The experimental method employed was that described in earlier papers.\* A slider having a spherical face is made to slide over a plate in an atmosphere of rigorously clean and dry air. The friction measured is static friction and the object of the experiments the determination of the effect of temperature. This has now been studied over a range of 15° C. to 110° C., and it may be said at once that the relations discovered are of a totally unexpected character.

More than one attempt to study the effect of temperature was defeated by the fact that lubricating vapours were given off from the walls of the chamber in which the plate and slider were enclosed. This difficulty was completely removed by using a chamber with double walls, the inner wall being a continuous sheet of nickel. Between the walls were placed the electric grids for heating the chamber. The stream of dry air with which the chamber was flooded was also heated by being passed through a tube of silica, which was maintained at the required temperature by a coil of wire through which a current was passing. The temperature of the stream of air and the temperature of the chamber were recorded electrically.

Temperature might influence friction by altering the state of the solid faces or of the lubricant; it was, therefore, necessary to study clean faces first.

*Clean Faces.*

Glass was found to be totally unsuitable for use because the physical state of its surface was profoundly altered by a relatively small rise of temperature. The figures in Table I illustrate this.

Table I.—Glass.

| Time elapsed. | Temperature (° C.). | Pull.    | $\mu$ . |
|---------------|---------------------|----------|---------|
| 5 minutes     | 15·5                | 25·5 gm. | 0·94    |
| 30 "          | 15·5                | 25·5 "   | 0·94    |
| 70 "          | 73                  | 13·6 "   | 0·51    |
| 100 "         | 74                  | 12·1 "   | 0·46    |
| 130 "         | 74                  | 12·1 "   | 0·46    |
| 180 "         | 15·5                | 12·0 "   | 0·46    |
| 240 "         | 15·5                | 12·0 "   | 0·46    |

\* 'Proceedings,' A, vol. 100, p. 550.

It will be noticed that the coefficient of friction ( $\mu = \text{pull} \div \text{weight of slider}$ ) falls as the temperature rises, and that the changed state of the surface which this indicates is not reversed when the temperature falls.

The fall in friction was greater the higher the temperature to which the glass was exposed. Thus glass at  $74^\circ$  reached a steady state in about 30 minutes with  $\mu = 0.46$ , but at  $110^\circ$  in 45 minutes with  $\mu = 0.36$ . The effect is due to the formation of a film which prevents water from wetting the surface, and which cannot be removed by soap and water; it is, however, destroyed by hot chromic acid and the friction then returns to the full "clean" value characteristic of the particular sample of glass.

*Quartz*, when cleaned in the way ordinarily used for glass, namely, by heating in a strong solution of chromic acid and rinsing in tap water, behaved like glass as the values given in Table II show:—

Table II.—Quartz.

| Time.     | Temperature ( $^\circ$ C.). | $\mu$ .      |
|-----------|-----------------------------|--------------|
| 0 minutes | 17                          | 0.73         |
| 30 "      | 17                          | 0.75         |
| 65 "      | 72                          | 0.13         |
|           |                             | (slow glide) |
| 120 "     | 110                         | 0.09         |
| 175 "     | 20.5                        | 0.68         |

By this time we were aware of the fact that the friction of steel and bismuth is not affected by temperature. This suggested that the behaviour of quartz might be due to a film obstinately adhering to the surface, and not to the substance itself. The suggestion proved to be correct, since the fall in friction observed with rise of temperature did not appear when the quartz faces were vigorously rubbed with the fingers under a stream of water, after having been heated in the chromic acid bath. It is not unlikely that this film on quartz, which resists hot chromic acid and needs actual traction for its removal, is itself a glass due to surface reaction of the silica with alkali from the air or from polishing or cleansing substances.

The values in Table III are for fully cleaned quartz. It will be noticed that the coefficient of friction of clean quartz is less than that of glass.

*Steel and bismuth*, when clean, show no change whatever in the friction over the range of temperature which was tried.

The result of these experiments with clean faces then is that the friction of a face of quartz, steel or bismuth, when thoroughly freed from adherent films, is sensibly independent of temperature over the range  $15^\circ$  to  $110^\circ$  C.

Table III.—Quartz.

| Time.     | Temperature (° C.). | $\mu$ . |
|-----------|---------------------|---------|
| 0 minutes | 16·5                | 0·770   |
| 45 "      | 16·5                | 0·770   |
| 120 "     | 110                 | 0·765   |
| 145 "     | 110                 | 0·765   |
| 210 "     | 18                  | 0·763   |

*Lubricated Faces.*

Steel and quartz alone were used in these experiments; there is, of course, no reason to suppose that bismuth would have behaved differently.

*Surfaces Flooded with Lubricant.*—When the lubricant was fluid throughout the whole temperature range the friction was independent of temperature.

The following values were given, without sensible change, over the range 15° C. to 110° C. :—

Table IV.

| Lubricant.            | Steel.  | Quartz. |
|-----------------------|---------|---------|
|                       | $\mu$ . | $\mu$ . |
| Undecane .....        | 0·34    | 0·49    |
| Caprylic acid .....   | 0·20    | 0·306   |
| Pelargonic acid ..... | 0·14    | 0·238   |
| Butyl alcohol .....   | 0·39    | 0·545   |
| Octyl " .....         | 0·29    | 0·457   |
| Undecyl " .....       | 0·23    | 0·39    |

When the lubricant was solid over part of the range the effect of temperature was different below and above the melting point of the solid. The friction was always found to fall with rise of temperature up to the melting point. At this point there was a remarkable discontinuity, the friction falling to zero. When the lubricant was fully melted the friction suddenly reappeared at a higher level than before the discontinuity, and was constant over the remainder of the temperature range. When the temperature was allowed to fall from the highest point (110° C.) there was no change in friction until the melting point was again reached, when there was a sudden fall, but not to zero. Below this point it was not possible to go, because the slider became set fast in the solid mass of lubricant. These relations are illustrated in Table V, and by the curve in the diagram.

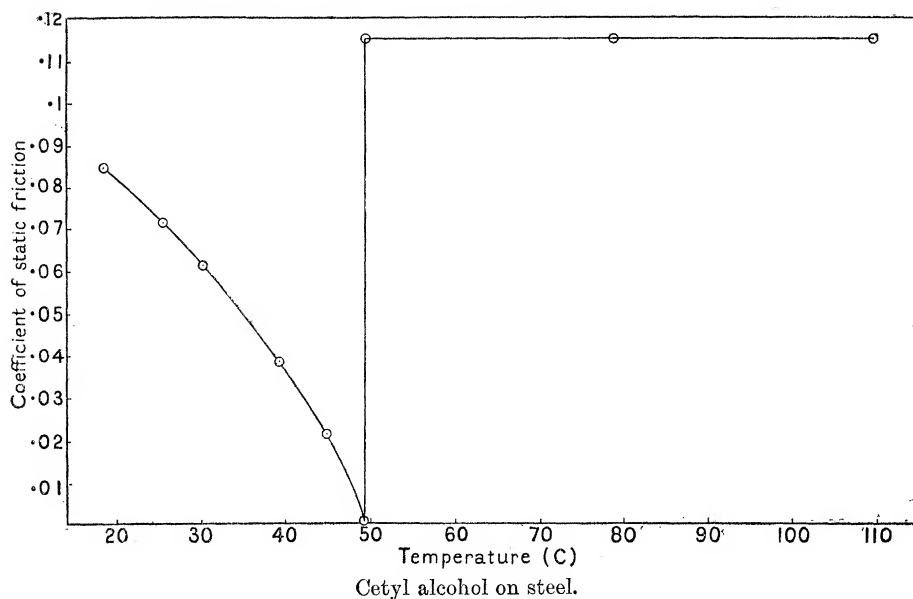
The lubricant was applied by placing a few crystals of the solid on the

plate in the chamber which had already been heated above the melting point. The slider was placed on the plate now covered by a layer of fluid lubricant and the chamber allowed to cool slowly. When at room temperature, the slider was lifted from the plate with the whole visible mass of lubricant attached to it, replaced, and observations of the friction were then taken.

Nonadecane, docosane, tetracosane, decoic acid, undecoic acid, palmitic acid, stearic acid, and cetyl alcohol were tried. It will be sufficient to give the figures for one of these:—

Table V.—Palmitic Acid on Quartz. Melting Point, 62° C.

| Time.      | Temperature (° C.). | $\mu$ .                |
|------------|---------------------|------------------------|
| 45 minutes | 19·0                | 0·163                  |
| 65 "       | 28·4                | 0·140                  |
| 90 "       | 34·2                | 0·121                  |
| 110 "      | 39·8                | 0·098                  |
| 145 "      | 48·5                | 0·063                  |
| 160 "      | 54·5                | 0·038                  |
| 195 "      | 59·3                | 0·021                  |
| 210 "      | 62·0 (melting)      | 0·0                    |
| 212 "      | 62·0 (liquid)       | } less<br>than<br>0·03 |
| 245 "      | 110                 |                        |
| 290 "      | 63                  |                        |
| 295 "      | 61·8 (solidifying)  |                        |



The discontinuity at the melting point would appear to be due to the fact that, when the lubricant is still solid, the friction that is measured is

that of the lubricant on itself. This might well be expected to fall with rise of temperature so near the melting point. This conclusion derives a certain amount of support from the fact that the coefficient of friction of a glass slider on the solid paraffin  $C_{24}H_{50}$  is, at  $16^\circ$ ,  $\mu = 0.07$ , whilst the coefficient of glass on glass lubricated by a film of this paraffin is  $\mu = 0.325$ . Above the melting point the friction, on the contrary, is that of solid faces, as modified by a primary film of the particular lubricant. In order to eliminate the friction of the lubricant on itself, films of insensible thickness were deposited on the faces from solutions in ether. The discontinuity now disappeared, and the friction became constant over the whole range, both when the temperature was rising and when it was falling, and we may therefore conclude that, over the range of temperature  $15^\circ$  to  $110^\circ$  C., the friction of quartz and of steel, lubricated with normal paraffins and the related normal acids and alcohols, is sensibly independent of temperature.

Table VI.

| Lubricant.           | Temperature (° C.). | $\mu$ .                                          |
|----------------------|---------------------|--------------------------------------------------|
| Steel.               |                     |                                                  |
| $C_{19}H_{40}$ ..... | 15.6-110            | 0.179                                            |
| $C_{22}H_{46}$ ..... | 17.3-110            | 0.110                                            |
| $C_{24}H_{50}$ ..... | 17.0-110            | 0.068                                            |
| Cetyl alcohol .....  | 16.5-110            | 0.1143                                           |
| Decoic acid .....    | 15.0- 75            | 0.075                                            |
| Undecoic acid.....   | 15.0- 80            | } Negligible—glides with<br>weight of scale pan. |
| Palmitic „ .....     | 16.5-110            |                                                  |
| Stearic „ .....      | 17.0-110            |                                                  |
| Quartz.              |                     |                                                  |
| $C_{19}H_{40}$ ..... | 15.0-110            | 0.324                                            |
| $C_{22}H_{46}$ ..... | 15.8-110            | 0.26                                             |
| $C_{24}H_{50}$ ..... | 16.5-110            | 0.23                                             |
| Cetyl alcohol .....  | 19.0-110            | 0.276                                            |
| Decoic acid.....     | 17.2-110            | 0.18                                             |
| Undecoic acid.....   | 16.5-110            | 0.114                                            |
| Palmitic „ .....     | 16.5-110            | } Glides with weight of<br>scale pan.            |
| Stearic „ .....      | 18.3-110            |                                                  |
| Myristic „ .....     | 18.0-110            |                                                  |

The curious fact that there is no static friction at the melting point of a lubricant when the faces are flooded with it is not so readily explained. The phenomenon is observed when the lubricant is partly solid and partly melted. We may therefore picture to ourselves the solid faces, each covered by its adherent film, and separated during melting by a mixture of solid and

fluid lubricant, and the latter is continually being supplied at the expense of the former. Under these conditions the friction would be fluid friction, and therefore static friction would be absent; and the friction of the solid faces, as lubricated by the particular lubricant, would not reappear until melting was complete and all the fluid squeezed out by the weight of the slider, leaving the solid faces separated by two primary films of lubricant, as described in the earlier paper. The fact that the static friction reappears instantly and at full value confirms the view there taken that solid friction does not change gradually to fluid friction, but that the one changes to the other abruptly at a certain critical thickness of the film. The state of the material in these lubricating films is determined by the attraction field of the solid as well as by the mutual attraction of the atoms and molecules of which it is composed. Since there is no change in the curve friction/temperature at the melting point of the lubricant, we may suppose that the former is more important than the latter. The fact, known since Leslie's time, that heat is liberated when a solid is wetted by a fluid, shows that the degree of freedom of a molecule in these films is less than that of one in the interior of a fluid mass of the same lubricant.

The curves connecting static friction with molecular weight, which were given in the last paper, cut the base line; that is to say, above a molecular weight which is different for each chemical series, static friction should vanish. More careful measurements made since the last paper was written show that this actually is so when the lubricant is present only as a film of insensible thickness. Then the slider moved with the smallest weight which could be applied, namely, 0.7 gm. It moved slowly, as might be expected, since the accelerating force was so small—the observed rate being of the order 0.4 mm. per hour.

When the lubricant is present in excess there frequently is resistance to movement due to surface tension, for consider a small drop symmetrically disposed about the area of contact between slider and plate. Movement of the slider will increase the area of the interfaces between the drop and air and the drop and the plate. In certain cases this absorbs work. For example, a steel slider in a small drop of melted palmitic acid on a steel plate needed a weight of 3.6 gm. to move it, when the drop was smeared about the plate a weight of 0.9 gm. was sufficient, but when the acid was present on the surfaces only as a film of insensible thickness the weight of the scale pan (0.7 gm.) alone sufficed to make the slider glide slowly.

---